

Evidence for $WZ/WW \rightarrow \ell\nu + \text{Heavy Flavors}$ Vector Boson Production in 7.5 fb^{-1} of CDF Data

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This contribution describes a search for the associated production of Standard Model vector bosons WZ where the W boson decays leptonically ($W \rightarrow \ell\nu$) and the Z boson decays to a heavy flavor quark pair ($Z \rightarrow b\bar{b}, c\bar{c}$). At least one identified (“tagged”) heavy flavor jet in the final state is required. Given the small di-jet invariant mass separation between the W and the Z resonances, the production of WW events where one W decays leptonically and the second W decays into an heavy flavor jet (e.i. $W^+ \rightarrow c\bar{s}$) contributes to our the signal.

This search uses data collected with the CDF II detector at the Tevatron Collider at Fermilab, and corresponding to an integrated luminosity of approximately 7.5 fb^{-1} . Events consistent with the signature of a charged lepton (electron or muon), large missing transverse energy and exactly two jets, of which at least one is required to contain a secondary vertex displaced from the jet origin, are selected. A multivariate discriminant based on the Support Vector Machine algorithm is used to reduce greatly the multi-jet background contamination.

We observe a signal of significance of 3.03σ over the background only hypothesis. A cross section of $1.085^{+0.26}_{-0.40}$ times the expected Standard Model value for the combined WZ/WW production and decay into heavy flavors is measured, consistent with the Standard Model prediction.

This contribution describes the search for $p\bar{p} \rightarrow WZ \rightarrow \ell\nu b\bar{b}$ (or $\rightarrow \ell\nu c\bar{c}$). The signature for this process is a W -boson, decaying to a high- P_T charged lepton and neutrino, plus a Z -boson decaying to two jets containing heavy flavor quarks. This signature is very similar to the one used in the search for a low mass Higgs boson ($M_H < 140 \text{ GeV}/c^2$), where the $H \rightarrow b\bar{b}$ branching fraction is large and the particle is produced in association with a W boson. Therefore the identification of the WZ signal in the channel containing heavy flavor jets represents a benchmark in the search for the low mass Higgs.

We base our signal to background discrimination on the *invariant mass* distribution of high- P_T jet pair entering in our selection, therefore, since we use a secondary vertex finding algorithm to identify b -quark produced jets (b -tagging), we also consider the process $WW \rightarrow \ell\nu c\bar{s}$ as part of our signal. We identify about 8% of the secondary vertices produced by charmed-hadrons coming from WW events. On the other hand, we identify more than 60% of WZ decaying into heavy flavors.

The main backgrounds for the signal processes include: W +jets production (where the jets contain either tagged heavy flavor or mis-tagged light flavor), top quark production and multi-jet production, where one jet is misidentified as a lepton. As we increase the acceptance of our signal using several triggers and lepton identification algorithms, we use a multi-jet rejection algorithm based on a Support Vector Machine discriminant exploiting the kinematic of the event.

The CDF detector is described in detail in [1].

I. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of 7.5 fb^{-1} collected with the CDFII detector between March 2002 and March 2011. We select events consistent with the signature of a W boson leptonic decay, large missing transverse energy and exactly two energetic b -quark jets. We accept tight charged lepton candidates, loose charged lepton candidates and isolated tracks; by construction these lepton categories are orthogonal to each other. The data containing tight leptons are collected with an inclusive lepton trigger that requires an electron (muon) with transverse energy, E_T , greater than 18 GeV (transverse momentum, P_T , greater than 18 GeV/c). The data containing loose leptons and isolated tracks are collected using triggers based on missing transverse energy (\cancel{E}_t) and jet information.

In the following we refer to these categories of events:

- CEM: central tight electrons;
- CMUP and CMX: central tight muons;
- EMC (extended muon categories): loose muons and isolated track lepton candidates.

We select events consistent with a W -boson decay plus two energetic b -quark jets. The W -boson events are selected by requiring a single, isolated electron (muon) with $E_T(P_T) > 20$ GeV(GeV/c) central in the detector (absolute pseudorapidity in detector coordinates system, $|\eta_{Det}|$, less than 1.1) and $\cancel{E}_t > 20$ GeV (> 10 GeV for CMUP and CMX). Exactly two central ($|\eta_{Det}| < 2.0$) jets with $E_T^{corr} > 20$ GeV (energy corrected for detector effects) are required. In order to improve the separation of signal and background events, we require that at least one of the two jets is identified to originate from a heavy quark by the Secondary Vertex tagger SecVtx [2]. We further suppress non- W multi-jet background using a multivariate technique (see Section I A)

A. Suppression of non- W Multi-jet Background

A fake W -boson-like signature can be generated when one jet fakes a high p_T lepton and \cancel{E}_t comes from jet energy mis-measurement. We developed a method to suppress this, so-called, multi-jet background using a multivariate technique based on the Support Vector Machine algorithm (SVM) [3]. We developed a software package, based on the LibSVM [4] library, able to perform algorithm training, variable ranking, signal discrimination and robustness test.

Although we trained the discriminant on a central electron sample, we apply it to all our selected data-sets (electron, tight muons, loose muons and tracks) because the algorithm is based only on kinematic variables. We achieve a large reduction of the multi-jet contamination in all the lepton categories, maintaining a very high efficiency on the signature $p\bar{p} \rightarrow \ell\nu + jj$.

1. Summary and Results of the SVM Training

The test and training sample used to develop the multi-jet veto was built with the following W selection requirements:

- one high energy, isolated central electron;
- exactly two jets reconstructed with $|\eta_{Det}| < 2.0$ and $E_T^{corr} > 20$ GeV;
- presence of missing transverse energy as signature of the escaping neutrino.

Multi-jet events can pass the same requirements, if one of the jets fakes the electron and the \cancel{E}_t is either mis-measured by the detector, faked by mis-identified (or undetected) minimum ionizing particles or produced by neutrinos associated with decay of heavy quarks. We built our training-set using 8000 signal events and 4000 background events (to emulate the data composition):

signal: $W + 2$ partons Alpgen Monte-Carlo [5], where the W is forced to decay into electron and neutrino. We have $\approx 10^5$ generated events and we keep $\approx 9 \times 10^4$ events as a control sample (i.e. not used for training).

background: due to the nature of the background (a mixture of physics processes and detector response), there is no simulated models that can be trusted to provide the accurate description needed for training. Therefore we use a data-driven approach to obtain a suitable sample: we select events with a fake electron by reversing some of the “electron quality” requirements (at least 2 out of the 5 cuts), used to identify the shape of the electromagnetic shower in the calorimeter. This selection is named “anti-electron” and produces a multi-jet enriched sample which is, however, statistically limited to a few thousands of events. Furthermore, we cannot rely on the modeling of the variables directly correlated to the reversed electron cuts.

The variable-sorting algorithm produced an optimal SVM using 6 variables as input features:

- W related variables: Lepton P_T , \cancel{E}_t , $\Delta\phi(e, \cancel{E}_t^{raw})$;
- Jet related variables: E_T^{raw} and E_T^{corr} of second most energetic jet;
- Global variables: \cancel{E}_t significance (a variable that relates \cancel{E}_t with jet corrections).

The best SVM configuration reduce the fraction of background in data to $f_{bkg}^{Data} < 10\%$, and it has an efficiency on signal events of $\epsilon_{sgn}^{MC} \approx 95\%$ (from MC).

II. BACKGROUNDS

Since our final state has the signature of a charged lepton, \not{E}_t and two jets (a W boson and jets signature), the following background sources are considered:

Non-W/Multi-jet : a W -boson-like signature is generated when one jet fakes a high P_T lepton and \not{E}_t is generated through jet energy mis-measurement (more details can be found in Section I A).

W + Mistags: this background occurs when one or more light flavor jets produced in association with a W boson are mistakenly identified as a heavy flavor jet by the b -tagging algorithm. Mistags are generated because of the finite resolution of the tracking detectors, material interactions, or from long-lived light flavor hadrons (Λ and K_s) which produce real displaced vertices.

W+ Heavy Flavor: these processes ($W + b\bar{b}$, $W + c\bar{c}$ and $W + c$) involve the production of heavy flavor quarks in association with a W boson.

Other Electroweak Backgrounds: additional small but non-negligible background contributions come from single top quark and top quark pair production, Z boson + jets production.

We determine the amount of selected W +jets events for each lepton category by fitting the \not{E}_t distribution of the pretag data control sample: for Top and Electroweak components the MC templates are normalized to the theoretical expectation while for W +jets and Non- W the normalization is free to float in the likelihood fit used. The following samples are used to produce the non- W templates:

- modified anti-electrons for central electron fakes ;
- non-isolated (iso > 0.2) tight muons for the central tight muons fakes;
- non-isolated (iso > 0.2) loose muons to mimic the EMC categories.

As expected after the efficient multivariate multi-jet rejection cut, the fits return a very small multi-jet contamination (ranging from 2.2% to 7.5% depending on the lepton category), .

The b -tagged W +Heavy Flavor (HF) component is extracted from the total W +jets pretag sample: the total W +jets is composed by a large set of Alpgen+Pythia [7] Monte Carlo weighted by their LO production cross section, the HF fractions are then extracted and scaled for the NLO contribution and b -tagging algorithm efficiency.

We estimate the normalization of $W +$ Mistags background by applying the mistag matrix to the pretag data after subtracting the non- W , top, diboson, Z +jets and W +HF contributions. We model the $W +$ Mistag kinematics and shapes using $W +$ Light Flavor Monte Carlo events weighting each event for the mistag probability.

The top quark and other electroweak backgrounds are normalized directly to their theoretical cross sections, calculated at next-to-leading order.

Finally the residual tagged Non- W component is fitted to the data together with a template of all the other backgrounds: the two normalizations are free to float and the multi-jet one is extracted.

More details on the background estimate can be found in Ref [6].

Tables I, II and III summarize the number of observed and expected events in the W +2 jets sample, for all lepton categories, before requiring a b -tag, with one b -tag and with two b -tags, respectively.

III. $M_{inv}(jet1jet2)$ DISTRIBUTION

The signal discrimination is based on the invariant mass of the two jets ($M_{inv}(jet1jet2)$) in the event. Candidates are separated into four statistically independent channels: tight leptons (CEM+CMUP+CMX) with 1 SecVtx tag, EMC lepton candidates with 1 SecVtx tag, tight leptons with 2 SecVtx tags and EMC with 2 SecVtx tags. The $M_{inv}(jet1jet2)$ distributions for single tagged events for tight leptons and EMC leptons are shown in Figure 1 and Figure 2 respectively. The corresponding distributions for events with two tags are shown in Figure 3 and Figure 4. These four distributions are used for the final signal to background discrimination. The $M_{inv}(jet1jet2)$ plots shown here are the ones returned by the final fit, with a full treatment of the correlated systematic effects (see next paragraph for a complete description).

IV. STATISTICAL ANALYSIS

Since the process $WZ/WW \rightarrow \ell\nu + \text{Heavy Flavors}$ was never observed before, we start evaluating 95% C.L. limits on a potential signal. The following systematic uncertainties (for background and signal) are taken into

TABLE I: Summary of pretagged observed and expected events in the W+2 jets sample in 7.5 fb^{-1} of data.

Channel	CEM	CMUP	CMX	EMC	All Channels
Pretag Data	61596	29036	18878	27946	137456
$t\bar{t}$	498 ± 46	271 ± 25	133 ± 17	418 ± 39	1320 ± 95
Single Top s	123 ± 11	66 ± 6	32 ± 4	87 ± 8	308 ± 22
Single Top t	191 ± 21	101 ± 11	52 ± 7	130 ± 14	474 ± 37
WW	1580 ± 132	804 ± 67	465 ± 56	822 ± 70	3672 ± 253
WZ	216 ± 20	118 ± 11	75 ± 10	147 ± 14	556 ± 40
ZZ	4.1 ± 0.3	6.1 ± 0.5	3.7 ± 0.4	8.1 ± 0.7	22 ± 2
Z+jets	1185 ± 147	1690 ± 209	1084 ± 163	1881 ± 234	5840 ± 728
W + $b\bar{b}$	1892 ± 759	905 ± 362	540 ± 216	843 ± 339	4180 ± 932
W + $c\bar{c}$	4041 ± 1622	1873 ± 750	1195 ± 479	1724 ± 693	8833 ± 1975
W + cj	3174 ± 1274	1543 ± 618	935 ± 375	1117 ± 449	6770 ± 1532
W +Light Flavor	44509 ± 2785	20987 ± 1104	13661 ± 741	18645 ± 1274	97803 ± 3339
Non-W	4182 ± 1673	672 ± 269	702 ± 281	2122 ± 849	7678 ± 1916

TABLE II: Summary of observed and expected events with one secondary vertex tag (SecVtx), in the W+2 jets sample, in 7.5 fb^{-1} of data.

Channel	CEM	CMUP	CMX	EMC	All Channels
Pretag Data	61596	29036	18878	27946	137456
$t\bar{t}$	201.3 ± 19.6	109.8 ± 10.7	55.0 ± 7.1	171.9 ± 16.9	538 ± 53
Single Top s	52.9 ± 4.8	28.2 ± 2.6	14.0 ± 1.8	38.0 ± 3.5	133 ± 12
Single Top t	71.4 ± 8.4	37.4 ± 4.4	19.8 ± 2.9	49.5 ± 5.8	178 ± 21
WW	68.0 ± 9.4	33.3 ± 4.6	20.3 ± 3.3	38.4 ± 5.3	160 ± 22
WZ	21.8 ± 2.3	11.5 ± 1.25	7.4 ± 1.0	14.1 ± 1.6	54.7 ± 5.9
ZZ	0.44 ± 0.04	0.65 ± 0.06	0.42 ± 0.05	0.86 ± 0.08	2.4 ± 0.2
Z+jets	27.9 ± 3.5	43.0 ± 5.5	27.3 ± 4.2	65.0 ± 8.4	163 ± 21.1
W + $b\bar{b}$	632.9 ± 254.2	309.8 ± 124.1	192.3 ± 77.1	308.9 ± 124.3	1444 ± 579
W + $c\bar{c}$	331.0 ± 133.7	155.1 ± 62.5	96.2 ± 38.8	164.2 ± 66.4	747 ± 301
W + cj	259.9 ± 105.0	127.8 ± 51.5	75.3 ± 30.4	106.4 ± 43.0	569 ± 229
Mistag	605.2 ± 71.3	283.8 ± 31.7	181.0 ± 20.6	346.2 ± 39.2	1416 ± 146
Non-W	173.9 ± 69.6	45.8 ± 18.3	2.8 ± 1.1	100.9 ± 40.4	323.3 ± 129
Prediction	2446.6 ± 503.7	1186.2 ± 242.2	691.8 ± 148.7	1404.5 ± 242.6	5729 ± 1132
Observed	2332	1137	699	1318	5486
WW/WZ	89.7 ± 10.2	44.8 ± 5.05	27.7 ± 3.9	52.5 ± 5.9	214.8 ± 24.4

account as normalization nuisance parameters: JES, Alpgen Q^2 , b-tag scale factor, lepton identification and trigger efficiencies, multi-jet background normalization, NLO scaling of W+heavy flavor production, ISR/FSR (for signal only) and mistag uncertainty. In addition, JES and Q^2 are taken as shape systematics as well, where the interpolated shape variation is used as nuisance parameter. All the nuisance parameters are fitted to improve the sensitivity.

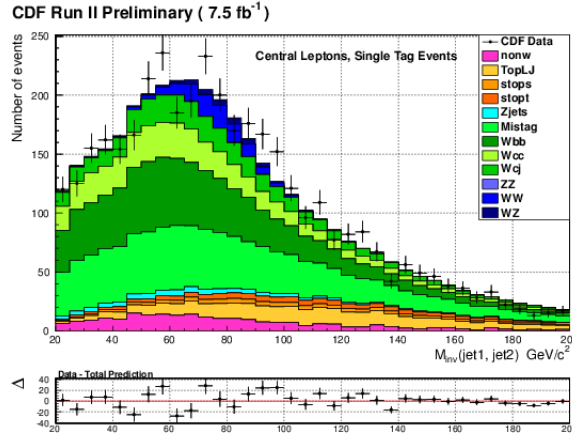
Expected 95% C.L. limits, assuming no SM WW/WZ production, are determined using Monte Carlo pseudo experiments based on expected yields varied within the assigned systematics. The normalization and shape uncertainties are integrated into the limit calculations. Table IV summarizes the median expected (and observed) 95% production limits (in units of SM WW + WZ cross section multiplied by branching fraction into heavy flavors).

Combining single-tagged and double-tagged results for all lepton categories, we find an expected limit of: $0.575^{+0.33}_{-0.31}$ times the SM prediction.

The observed limit, combining single-tagged and double-tagged results for all lepton categories, is 1.46 times the SM prediction.

TABLE III: Summary of observed and expected events with two secondary vertex tags (SecVtx), in the W+2 jets sample, in 7.5 fb^{-1} of data.

Channel	CEM	CMUP	CMX	EMC	All Channels
Pretag Data	61596	29036	18878	27946	137456
$t\bar{t}$	42.2 ± 6.1	22.2 ± 3.2	11.1 ± 1.9	34.4 ± 5.0	109.7 ± 15.8
Single Top s	14.1 ± 2.0	7.6 ± 1.1	3.7 ± 0.6	10.2 ± 1.4	35.6 ± 5.0
Single Top t	4.2 ± 0.7	2.3 ± 0.4	1.2 ± 0.2	3.1 ± 0.5	10.8 ± 1.7
WW	0.6 ± 0.1	0.26 ± 0.07	0.16 ± 0.04	0.33 ± 0.08	1.3 ± 0.3
WZ	4.0 ± 0.6	1.9 ± 0.3	1.4 ± 0.2	2.4 ± 0.4	9.6 ± 1.4
ZZ	0.06 ± 0.01	0.12 ± 0.02	0.09 ± 0.01	0.16 ± 0.02	0.43 ± 0.06
Z+jets	0.9 ± 0.1	2.0 ± 0.3	1.2 ± 0.2	3.1 ± 0.4	7.2 ± 1.0
$W + b\bar{b}$	81.9 ± 33.2	42.2 ± 17.1	23.4 ± 9.5	44.9 ± 18.2	192 ± 78
$W + c\bar{c}$	4.7 ± 1.9	2.3 ± 1.0	1.3 ± 0.5	2.8 ± 1.1	11.0 ± 4.5
$W + c\bar{j}$	3.7 ± 1.5	1.9 ± 0.8	1.0 ± 0.4	1.8 ± 0.7	8.3 ± 3.4
Mistag	3.2 ± 0.7	1.6 ± 0.3	0.9 ± 0.2	2.2 ± 0.4	7.8 ± 1.6
Non-W	7.9 ± 3.2	4.8 ± 1.9	0.1 ± 0.5	0.0 ± 0.5	12.8 ± 6.1
Prediction	167.3 ± 38.0	88.9 ± 19.6	45.4 ± 10.9	105.3 ± 21.5	406.9 ± 89.5
Observed	147	74	39	106	366
WW/WZ	4.6 ± 0.6	2.1 ± 0.3	1.5 ± 0.2	2.7 ± 0.4	10.9 ± 1.5


 FIG. 1: $M_{Inv}(jet1, jet2)$ distribution for the 1 SecVtx tag candidates, tight leptons (CEM+CMUP+CMX combined). The best fit of the systematic nuisance parameters are taken into account.

A. Sensitivity

To compute the significance of a potentially observed signal, we perform a hypothesis test, comparing the data to two hypotheses. The null hypothesis, H_0 , assumes Standard Model processes except $WW + WZ$ production. The second hypothesis, H_1 , assumes that the $WW + WZ$ production cross section and the branching ratio into heavy flavors are the ones predicted by the Standard Model. The likelihood ratio is defined as:

$$-2\ln Q = -2\ln \frac{p(data|H_1, \hat{\theta})}{p(data|H_0, \hat{\theta})} \quad (1)$$

where θ represents the nuisance parameters describing the uncertain values of the quantities studied for systematic error, $\hat{\theta}$ the best fit values of θ under H_1 and $\hat{\hat{\theta}}$ are the best fit values of the nuisance parameters under H_0 . We perform two sets of pseudo-experiments to determine the expected sensitivity to the signal [8], one assuming H_0 and a second one assuming H_1 . On each pseudoexperiment, the values of the nuisance parameters are chosen randomly based on the systematic errors. The distributions of the values of $-2\ln Q$ are shown in

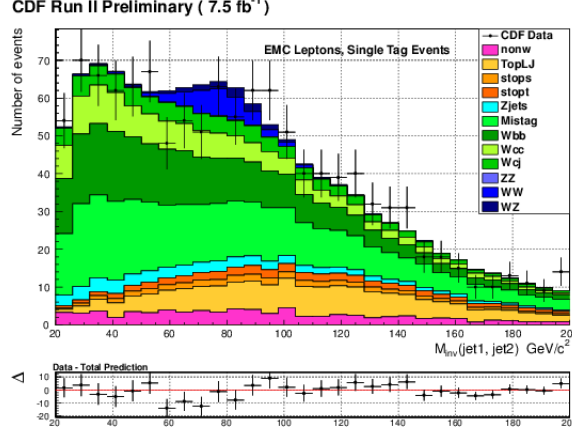


FIG. 2: $M_{Inv}(jet1, jet2)$ distribution for the 1 SecVtx tag candidates, extended muon categories (EMC). The best fit of the systematic nuisance parameters are taken into account.

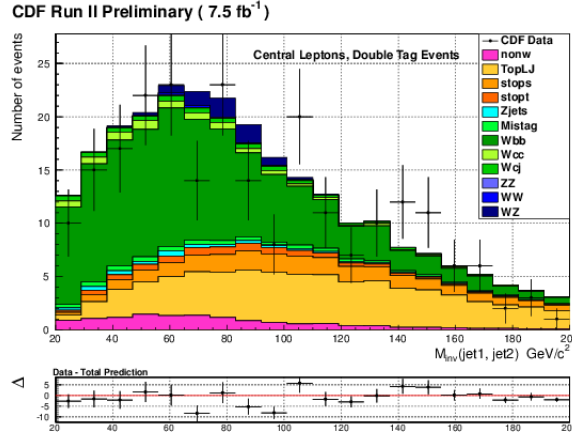


FIG. 3: $M_{Inv}(jet1, jet2)$ distribution for the 2 SecVtx tag candidates, tight leptons (CEM+CMUP+CMX combined). The best fit of the systematic nuisance parameters are taken into account.

Fig. 5 for the two hypotheses and the data.

The p -value is the probability that $-2\ln Q < -2\ln Q_0$, assuming the null hypothesis H_0 . The p -value was found to be 0.00120, corresponding to a 3.03σ excess.

The sensitivity of the analysis is computed as the median expected p -value assuming a signal is truly present. The median $-2\ln Q$ is extracted from the H_1 distribution, and the integral of the H_0 distribution of $-2\ln Q$ to the left of this median value is the median expected p -value. The value obtained is 0.00126, corresponding to 3.02σ .

TABLE IV: Expected limits for each lepton category, single and double tagged events, in units of the SM cross section for $WW + WZ$ production multiplied by the branching fraction into heavy flavors.

Tag and lepton category	Expected limit	Observed limit
1 tag Tight Leptons (CEM+CMUP+CMX)	$0.72^{+0.42}_{-0.38}$	2.07
1 tag EMC	$1.21^{+0.57}_{-0.46}$	1.70
2 tags Tight Leptons (CEM+CMUP+CMX)	$4.02^{+1.94}_{-1.50}$	3.03
2 tags EMC	$6.07^{+2.92}_{-2.20}$	8.59
All combined	$0.57^{+0.33}_{-0.31}$	1.46

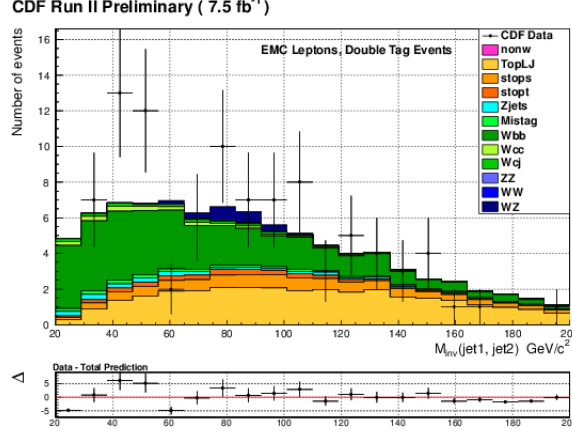


FIG. 4: $M_{inv}(jet1, jet2)$ distribution for the 2 SecVtx tag candidates, extended muon categories (EMC). The best fit of the systematic nuisance parameters are taken into account.

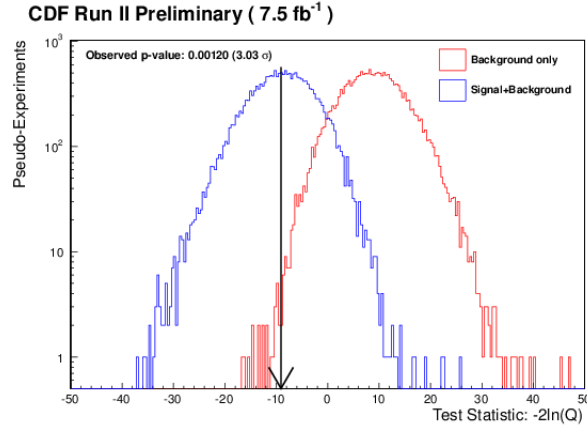


FIG. 5: Distributions of $-2\ln Q$ for the test hypothesis H_1 , which assumes Standard Model backgrounds plus Standard-Model $WW + WZ$ production and decay into heavy flavors (blue histogram), and for the null hypothesis, H_0 , which assumes no $WW + WZ$ (red histogram). The observed value of $-2\ln Q$ is indicated with a solid, vertical line. The plot is shown on a logarithmic scale. The p-value is the fraction of the integral of the H_0 curve to the left of the data.

B. $WW + WZ$ cross section measurement

In order to measure the $WW + WZ$ production cross section, a Bayesian marginalization technique is applied to the $M_{inv}(jet1, jet2)$ distribution in both 1 tag and 2 tags samples. The nuisance parameters are integrated out as described in [8]. The distribution of the posterior is shown in Fig. 6. The maximum of the posterior is taken to be the best fit value for the cross section measurement, and the $1-\sigma$ confidence interval is taken to be the shortest interval containing 68% of the integral of the posterior distribution. The resulting cross section measurement, in units of expected SM signal, is: $1.085^{+0.26}_{-0.40}$.

V. CONCLUSION

We analyzed 7.5 fb^{-1} of data looking for the $WW/WZ \rightarrow \ell\nu + HF$ signal in the $W + 2$ jets exclusive sample. We found an excess over background in the $M_{inv}(jet1, jet2)$ distribution looking at the Double tagged + Single tagged samples. Using a background only-hypothesis we found our result inconsistent with data: the significance of the observed signal corresponds to 3.03σ . We performed a measurement of the cross section for this process, that we found to be $1.085^{+0.26}_{-0.40}$ times the expected Standard Model prediction.

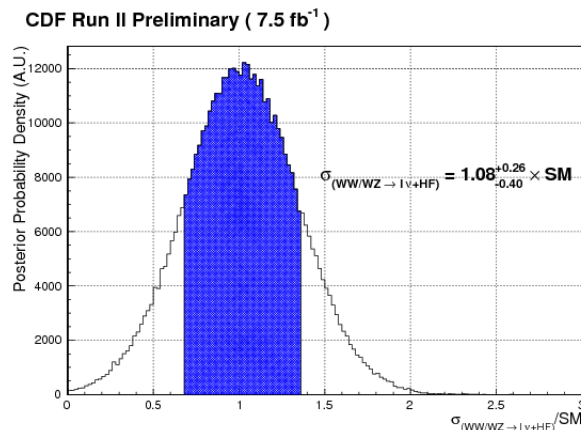


FIG. 6: The Bayesian posterior, marginalized over nuisance parameters, is shown. The maximum value is the central value of the cross-section. The blue area represents the smallest interval enclosing 68% of the integral of the posterior.

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